Mount Etna as a terrestrial laboratory to investigate recent volcanic activity on Venus by future missions: a comparison with Idunn Mons, Venus

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Abstract

The recently selected missions to Venus have opened a new era for the exploration of this planet. These missions will provide information about the chemistry of the atmosphere, the geomorphology, local-to-regional surface composition, and the rheology of the interior. One key scientific question to be addressed by these future missions is whether Venus remains volcanically active, and if so, how its volcanism is currently evolving. Hence, it is fundamental to analyze appropriate terrestrial analog sites for the study of possibly active volcanism on Venus. To this regard, we propose Mount Etna - one of the most active and monitored volcanoes on Earth - as a suitable terrestrial laboratory for remote and in-situ investigations to be performed by future missions to Venus. Being characterized by both effusive and explosive volcanic products, Mount Etna offers the opportunity to analyze multiple eruptive styles, both monitoring active volcanism and identifying the possible occurrence of pyroclastic activity on Venus. We directly compare Mount Etna with Idunn Mons, one of the most promising potentially active volcanoes of Venus. Despite the two structures show a different topography, they also show some interesting points of comparison, and in particular: a) comparable morpho-structural setting, since both volcanoes interact with a rift zone, and b) morphologically similar volcanic fields around both Mount Etna and Idunn Mons. Given its ease of access, we also propose Mount Etna as an analog site for laboratory spectroscopic studies to identify the signatures of unaltered volcanic deposits on Venus.

1. Introduction

Several new missions to Venus from NASA, ESA, Roscosmos, and potentially ISRO have been recently selected for launch. These missions led to opening a new era for the exploration of the "hellish twin" of our planet. In particular, the NASA Deep Atmosphere of Venus Investigation of Noble gases, Chemistry and Imaging (DAVINCI) mission (Garvin et al. 2022) and NASA Venus Emissivity, Radio Science, InSAR, Topography & Spectroscopy (VERITAS) mission (Smrekar et al. 2020), the ESA EnVision mission (Ghail et al. 2021, 2012, 2020), the Roscosmos Venera-D mission (Senske et al. 2017; Zasova et al. 2019), and the ISRO Shukrayaan-1 mission (Haider et al. 2018; Sundararajan 2021) will perform a detailed exploration of the surface and the atmospheric properties of Venus, both through orbiting and in-situ investigations. In summary:

- The DAVINCI mission will analyze the chemical composition and the vertical profile of the atmosphere of Venus with its descent probe performing high-resolution (e.g., 200 m down to 1 m resolution) sub-cloud imaging of one example of tessera terrain (Garvin et al. 2022), as well as multiple fly-by near-Infrared (NIR) emissivity mapping of tesserae and volcanic centers.

- The VERITAS mission will provide global infrared emissivity data (Helbert et al. 2013, 2018) along with a global radar map of the surface at an approximate resolution of 30 m, also providing an improved surface topography with a spatial resolution of 250 m and 5 m vertical accuracy (Smrekar et al. 2020). It will also determine the gravity field of the planet to degree and order >100 globally, which is a great improvement compared to the Magellan mission (Mazarico et al. 2019).

- The EnVision mission will provide high-resolution spectral data of the atmosphere and the surface in the spectral range 0.8 — 2.5 μm (Helbert et al. 2013, 2018), along with a high-resolution SAR map of the 20% of the surface at 30 m and subregions at 10 m (Ghail et al. 2021). The mission will investigate the subsurface of the planet with its Subsurface Radar Sounder (SRS) instrument (Bruzzone et al. 2020), and it will provide multipolarization data that will help analyzing possible pyroclastic deposits on Venus (Ganesh et al. 2021, 2022).

- The Roscosmos Venera-D mission will study the spectral properties of the atmosphere, and with a lander, it will also investigate the chemical composition and the interactions between surface and atmosphere (Senske et al. 2017; Zasova et al. 2019).

- The ISRO Shukrayaan-1 proposed mission is characterized by a fully loaded orbiter, whose instruments will analyze both the spectral characteristics of the surface to look for active volcanism and the chemical composition of the atmosphere (Haider et al. 2018; Sundararajan 2021). It will map the surface with a fully polarimetric S-band SAR (3.2 GHz) at 40 m resolution to characterize surface materials and a low frequency radar sounder for studying shallow subsurface stratigraphy (Widemann et al. 2023).

Moreover, China's Venus Volcano Imaging and Climate Explorer (VOICE) mission proposal is also being evaluated for selection. The mission would investigate surface geology and atmosphere of Venus through a S-band polarimetric SAR and a multispectral imager in the ultraviolet, visible, and near-infrared wavelengths (Dong et al. 2022).

Unlike the Earth, Venus does not currently display any sign of terrestrial-style plate tectonics. Moreover, its crust has been defined as a "stagnant lid regime" by previous researchers (Solomatov & Moresi 1996). In this regard, one of the major scientific debates of Venus is focused on whether the planet underwent a catastrophic eruptive event (Basilevsky & Head 1995; Ivanov & Head 2011;

Romeo & Turcotte 2010; Schaber et al. 1992) or more equilibrium volcanic resurfacing (Guest & Stofan 1999; Hansen & Young 2007; O'Rourke et al. 2014; Phillips et al. 1992) over its geologic history. To shed light on this debate, it is crucial for future missions to Venus to target areas of recent or potentially ongoing volcanic activity (Shalygin et al. 2015; Smrekar et al. 2020; D'Incecco et al. 2017, 2021a, 2022; Filiberto et al. 2020, 2021; Teffeteller et al. 2022; Brossier et al. 2020, 2021, 2022; Herrick & Hensley 2023). A comprehensive analysis of recent volcanic deposits on Venus can provide information about the possible presence and concentration of volatiles in its mantle, which is still being debated (Filiberto 2014; Karimi & Dombard 2017; Nimmo & Mckenzie 1998). As an example, previous works have suggested the possible occurrence of pyroclastic deposits on Venus, which would imply the presence of a hydrated mantle, where the volatiles may be represented by SO_2 or CO_2 rather than water (Ghail & Wilson 2013). A volatile-rich mantle would facilitate a steadier volcanic resurfacing, as it happens on Earth. In contrast, the absence of volatiles would cause overheating of the mantle, favoring a more catastrophic volcanism.

Compared to the average age of its surface, the young volcanic rises can be considered as some of the stratigraphically most recent areas of Venus (D'Incecco et al. 2021a, c, 2022; Stofan & Smrekar 2005). These regions are thought to be the surface manifestation of upwelling mantle plumes (Crumpler et al. 1993; Stofan et al. 1995; Stofan & Smrekar 2005), and they are generally characterized by the presence of several large volcanic structures, some of which may be recently or even currently active based on orbital measurements and experimental results (Smrekar et al. 2010; D'Incecco et al. 2017, 2021a,b,c; Filiberto et al. 2020, 2021; López et al. 2022, 2023; Brossier et al. 2020, 2021, 2022; Cutler et al. 2020; Teffeteller et al. 2022). In consideration of the large positive gravity anomalies observed at the young volcanic rises, Stofan and Smrekar (2005) also proposed that some of these regions may be presently dynamically supported. Based on the relation between uplift and the amount of extruded volcanic materials, Stofan et al. (1995) inferred that Imdr Regio might be a young volcanic rise still at an early stage of evolution. Subsequent observations by the ESA Venus Express VIRTIS of high 1 μm surface emissivity anomalies over the top and eastern flank of Idunn Mons, the major volcanic structure of Imdr Regio, located at 45°S, 215°E (Figure 1a), indicate the presence of chemically relatively unweathered surface volcanic deposits (Smrekar et al. 2010; Shalygin et al. 2015). The occurrence of present-day volcanic activity at Idunn Mons (especially if partially pyroclastic) would imply that the presence of a volatile-bearing mantle and a steadier volcanic resurfacing on Venus.

The wealth of data to be provided by the future missions will help to shed light on the volcanological history of Venus, providing important clues about if and how volcanism is currently evolving on this planet. For this purpose, it is important to focus on the identification of potentially active volcanic areas on Venus. Hence, it is crucial to find and analyze analog sites of active volcanism on Earth to aid selecting the science targets of orbiting and in-situ investigations to be performed by future missions to Venus, as proposed by the **A**nalogs for **VEN**us' **GE**ologically **R**ecent **S**urfaces (AVENGERS) initiative by D'Incecco et al. (2022, 2023).

In this manuscript, we present Mount Etna (i.e., Guest et al. 1984; Lopes & Guest 1982; Chester et al. 1985; Bonaccorso et al. 2004) as a laboratory for the identification of volcanically active areas on Venus, and we list the aspects why this volcano can be used as a suitable candidate for comparative studies with the Earth's twin planet (Eggers et al. 2022; D'Incecco et al. 2022). Compared to other potentially suitable candidate locations (i.e., East African Rift), Mount Etna is suggested in this work to be a better nominee for experimental and comparative studies, both in terms of data availability, applicability of the analog site, and ease of access. Furthermore, Mount Etna is also considered one of the best monitored volcanoes worldwide (Marchetti et al. 2019). The monitoring system provides a wealth of comprehensive and multiparametric datasets (Giammanco et al. 2018) that can be exploited to compare Venusian volcanism with terrestrial structures. Moreover, being a stratovolcano, hence characterized by a mixed type of volcanism and volcanic products (both effusive and explosives), Mount Etna is not only a suitable candidate site for detecting ongoing volcanism on Venus, but also offers the unique opportunity to test and compare the products of pyroclastic activity

on Venus, if such deposit types exist (i.e., Ghail & Wilson 2015; Campbell et al. 2017; Ganesh et al. 2021, 2022).

Based on SAR images and altimetry, we compare morphology, topography, and structural contexts of Mount Etna with Idunn Mons, which is a potentially active volcanic structure on Venus (Smrekar et al. 2010; D'Incecco et al. 2017, 2021a; Brossier et al. 2020). These two volcanoes share several common features, such as: i) the presence of multiple craters on their summits; ii) both volcanoes display widely distributed and extensive lava flows along their flanks; iii) both volcanoes show visual and morphologically comparable volcanic structures (i.e., similarities with the cinder cones and lava channels/tubes of Mount Etna).

Mount Etna can be also used as a terrestrial analog site for laboratory studies on visible and near-Infrared (VNIR) and Raman spectra from both altered and unaltered lava flows samples (Eggers et al. 2022), which are particularly useful for comparative purposes as they can reveal specific spectral signatures for identifying chemically unweathered (fresh) volcanic deposits on Venus. In section 4, we showcase the preliminary results of the laboratory analyses from the samples retrieved during the geologic fieldtrip we conducted on Mount Etna in January 2021 (Eggers et al. 2022, 2023). The detailed results of these laboratory studies will be discussed in a companion manuscript, whose preliminary results have been already presented by Eggers et al. (2022; 2023). Moreover, the DAVINCI's Venus Descent Imager (VenDI) NIR descent imaging system (Garvin et al. 2022) will produce band-ratio composite "maps" of Venus surfaces under the clouds at blur-corrected spatial scales as fine as a few meters with reflectance-based datasets (0.74 to 1.03 μm) that can be compared with laboratory data as the ones presented by Eggers et al. (2022, 2023), and others.

In section 5, we propose the possibility to use Mount Etna as the test site for drilling operations and in-situ elemental analyses to be operated by a future lander, such as the one of the Roscosmos Venera-D mission (similar to those successfully demonstrated on Venera 13, 14 and Vega 1, 2 by the USSR in the 1980s).

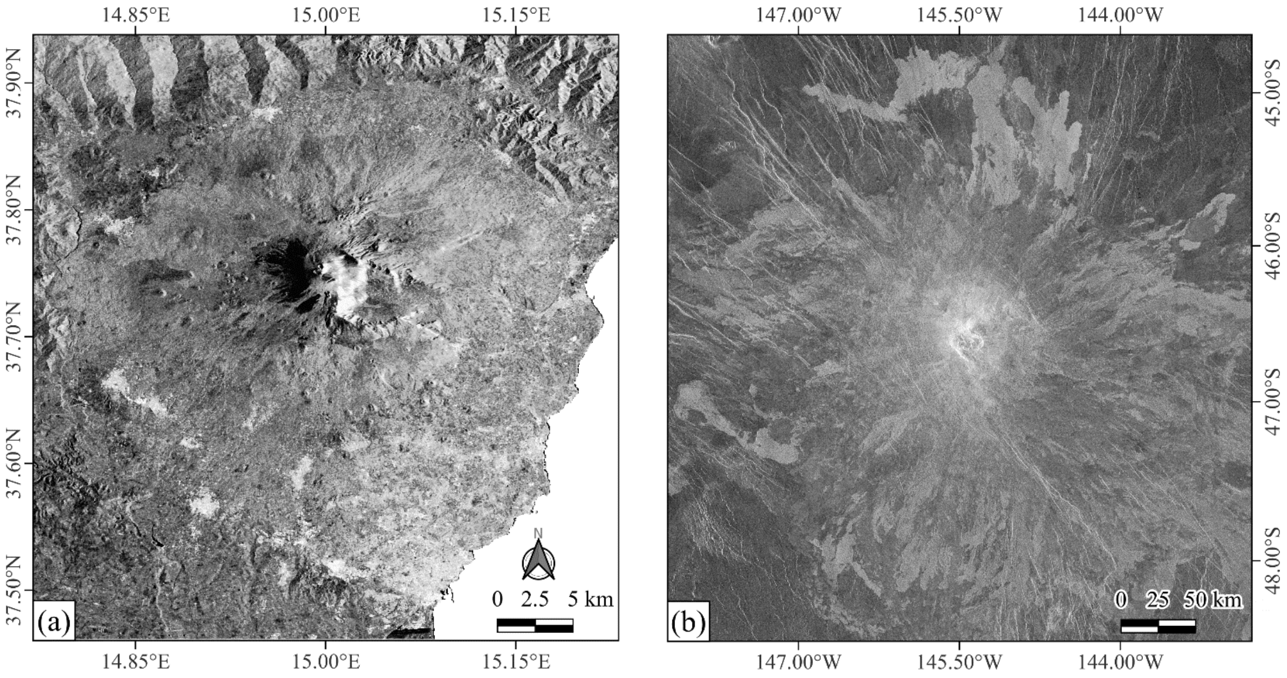

Figure 1: a) Mt. Etna, Sicily - Italy. ESA Sentinel-1A C-Band, Ground Range Detected High-Resolution (GRDH) right-look SAR Ascending, Resolution ~75m, ~35° incidence angle, λ 5.55 cm, (downsampled for consistency using a bi-linear interpolation). b) Idunn Mons in Imdr Regio - Venus. Magellan (S-band) left-look SAR scene - Resolution ~75m, ~25° incidence angle, λ 12.6 cm.

2. Volcanological history of Mount Etna

Mount Etna is the largest and most active sub-aerial composite volcano in Europe, situated on the eastern coast of Sicily, Italy, 37°30′ to 37°55′ North and 14°47′ to 15°15′ East (i.e., Branca et al. 2011a,b). Volcanism of the Etna region started around 500 ka ago and it is divided into four main phases according to the recent geological and radiometric investigations (Branca et al., 2011a,b; De Beni et al., 2011). The present-day stratovolcano edifice started to form 60 ka ago, and it includes the largest eruptive center of Mount Etna, called Ellittico volcano. Overall, about 20 ka BP the Ellittico volcano reached the elevation of about 3600 m a.s.l. and the maximum areal expansion with a maximum diameter of about 45 km that corresponds to the diameter of the Etna edifice today. The activity of the Ellittico volcano ended around 15.5-15 ka BP with four caldera forming Plinian eruptions (Coltelli et al. 2000; Del Carlo et al. 2017) that formed a wide summit caldera. The effusive activity of the last 15,000 years has led to the formation of the current volcanic structure called the Mongibello volcano. About 9,200 years ago, a portion of the eastern slope of the Mongibello volcano was subjected to a series of large landslides that led to the formation of the wide depression of the Valle del Bove (Guest et al. 1984; Calvari et al. 2004; Malaguti et al. 2023). The eruptive activity of the last 15 ka, related to the Mongibello volcano, produced a thick succession consisting of superposed simple and compound lava flows (Lopes & Guest 1982) and a pyroclastic succession generated by several strombolian to sub-Plinian events (Del Carlo et al. 2004).
The eruptive style at Mount Etna of the last 2500 years gives rise to different types of lava flows (Branca and Abate, 2019); mostly of the a'a type, but pāhoehoe flows also occur within the oldest and historical lavas. The volcanic products are mainly alkali basalts and hawaiites (trachybasalts) with a relatively constant composition (Corsaro & Métrich 2016; Miller et al. 2017). Regarding the volcanic structures formed by the eruptive activity, Mount Etna is rich in monogenetic volcanic cones and lava channels/tubes (Calvari & Pinkerton 1999; Azzaro et al. 2012). At present, the volcanic activity is characterized by recurrent summit and flank eruptions (Del Negro et al. 2013) accompanied by a quasi-continuous emission of magmatic volatiles from the summit craters (Ferlito et al. 2014; Moretti et al. 2018).

3. Side to side comparison between Mount Etna and Idunn Mons

3.1 Topography

Mount Etna is an enormous landform by terrestrial standards with a base circumference of 140 km and an area of about 1200 km^2 (Branca et al. 2017). Its summit is composed of five craters, with the Southeast Crater (SEC) reaching a maximum altitude of 3357 m (± 3 m a.s.l.) (INGV 2021). Mount Etna is classified as a stratovolcano (or composite volcano). While it does approximate a vaguely conical shape, broadly characteristic of such landforms, its slopes are pitted with nearly 200 cinder cones, and its southeast quadrant of the volcano is dominated by the flank collapse of the Valle del Bove. Below 1800 m, the volcano's slopes are a gentle ~5°, but above this, the slopes average ~20° (Favalli et al. 1999; Aveni and Blackett 2022). Interpretation of altimetric data for Idunn Mons, in spite of the low spatial resolution of the available data (the altimeter footprint varies as a function of the latitude: at Idunn Mons the footprints 8-11 km along track (N- S) and 21-24 km cross-track (E-W), see Pettengill et al. 1991; Ford and Pettengill 1992), revealed that the topographic profile of the structure is characterized by slopes comparable to those of the lower flanks of Mount Etna, averaging ~4° (Figure 2).

With its 200 km in diameter, Idunn Mons is classified as one of the large volcanoes on Venus (Head et al. 1992; Ivanov et al. 2015). However, this classification is purely dimensional, and it does not consider the styles of volcanism associated with the composition of the erupted materials (López

2011). Idunn Mons appears to have gentler slopes than Mt. Etna, although the precision of this statement is limited by the relatively low resolution of the available Magellan radar altimetric data. The topography and slopes of Idunn Mons appear similar to those of basaltic shield volcanoes on Earth. However, the very different surface environmental conditions (90 bars CO_2 and 460°C) on Venus are likely to affect the final topography of an overall volcanic structure, with explosive volcanism likely to be inhibited but not necessarily impossible and increasingly likely with altitude (Shalygin et al. 2015; Head & Wilson 1986, Glaze 1999). The compositions of volcanic rocks have not been directly analyzed at Idunn Mons, but the average microwave emissivity values from the summit and flank lava flows are consistent with mafic materials such as anhydrous dry basalt (D'Incecco et al. 2017). Furthermore, rocks analyzed by the Venera and Vega probes at other sites on Venus revealed basalt and alkali-basaltic compositions (e.g., Surkov 1984; Kargel et al. 1993; Filiberto 2014). Specifically, the rock analyzed by Venera-13 is consistent with a terrestrial alkalic-basalt or hawaiite (Filiberto 2014). Furthermore, the chemical data provided by the Soviet Venera and Vega landers are consistent with the morphology of the surface materials they landed on, substantially characterized by volcanic plains. These derived compositions (from XRFS elemental analyses of single samples), though limited and with relatively large measurement error bars (Treiman 2007), are comparable, at least first order, to the range in compositions of volcanic rocks at Mt Etna.

The two volcanoes show a difference in extent, ranging from the ~30 km in diameter of Mount Etna to the ~200 km in diameter of Idunn Mons. In terms of morphology, indeed, Idunn Mons can better be associated to Terrestrial shield volcanoes, rather than to composite volcanoes like Mount Etna. However, physiography on Venus is generally gentler and more horizontally distributed than on Earth (Tanaka et al. 1997). The gentler physiography on Venus may be at least partially due to the different environmental conditions compared to Earth, with the 475 °C temperature and 90 bars of atmospheric pressure on the surface playing a role. For this reason, observing similar morphologies on two volcanic structures on Earth and Venus does not necessarily imply the same formation process or chemistry in the eruptive products. Therefore, it is necessary to carefully analyze exactly to what extent topography can be used as a comparison, and how far can that comparison be pushed.

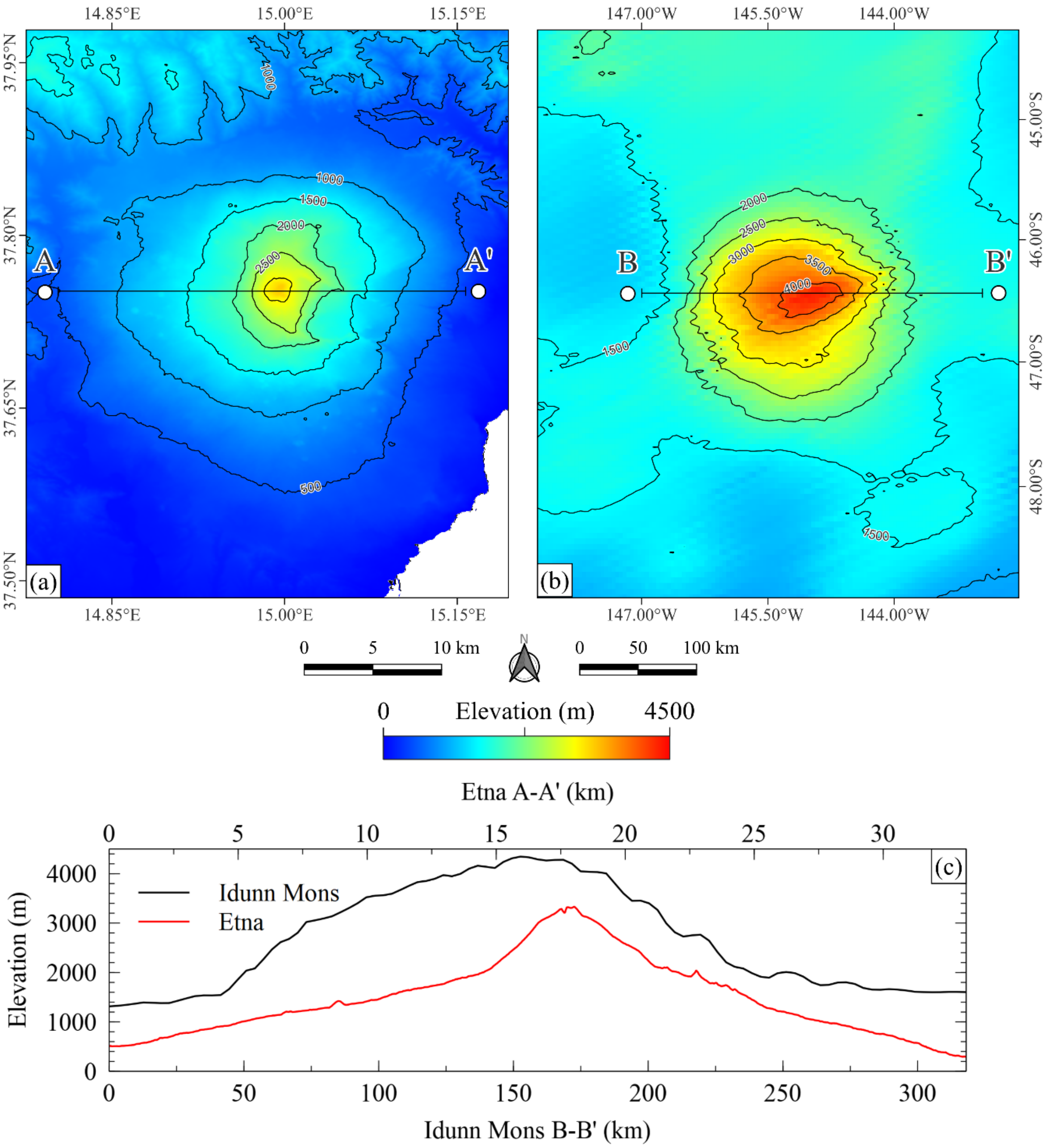

Figure 2: Topographic profiles of a) Mount Etna, based on a 10m resolution Digital Elevation Model (DEM) (DLR-INGV 2005) (A-A') and b) Idunn Mons from Venus Magellan radar altimeter data (GTDR), resampled at 4.6 km/pixel, at ~ 8 km along-track and 80m vertical precision (Ford and Pettengill, 1992). Global Topography 4641m (v2) (B-B').

3.2 Comparable surface volcanic features from the interpretation of SAR images

An intriguing term of comparison is given by the morphological similarities between the cinder cones on the western side of Mount Etna (Figure 3a), and individual volcanic features located on the flanks of Idunn Mons and similar ones that cluster in fields in Imdr Regio (Lang et al., 2020; López et al. 2023; Figure 3b). These features on Venus have been generally classified as small shields (Aubele & Slyuta 1990; Head et al., 1992; Aubele et al., 1992; Garvin and Williams 1992; Guest et al. 1992; Crumpler et al. 1997; Ivanov et al. 2015), but the processes behind the formation of these landforms are yet to be clarified. Unfortunately, the low resolution of the Magellan SAR scene for Idunn Mons only allows the identification of the largest of these volcanic features (⌀ > ~500 m), preventing the identification of a potentially denser distribution of such structures at smaller scales.

Moreover, it is noteworthy that a significant number of channels and channel-fed flows are identified on the summit area and flanks of Idunn Mons (López et al. 2022, 2023). Such channels may represent important mode of lava transport that is widely observed on Venus (Baker et al. 1992, 1997; Komatsu et al. 1993). Lava channel/tube activity has been observed also at Mount Etna (Bayley et al., 2006), further supporting the suitability of Mount Etna as a terrestrial analogue to better interpret and understand volcanic dynamics and processes shaping the Venusian landscape.

Considering the morphologic similarities between the cinder cones of Mount Etna (i.e Figure 3a) with some of the features observed in Idunn Mons (Figure 3b) and other parts of Imdr Regio, the occurrence of limited explosive volcanism is a process to be explored in the future. The problems of this type of volcanism on Venus were discussed by Head & Wilson (1992), but explosive volcanism has been described in other parts of the planet (Ghail & Wilson 2013; Airey et al. 2015; Ganesh et al. 2021, 2022). Mount Etna seems to be a suitable example, inter alia, for the identification of composite styles of volcanism on Venus, presenting several benefits for the identification and validation of experimental studies aimed at better understanding volcanic processes and features on Venus

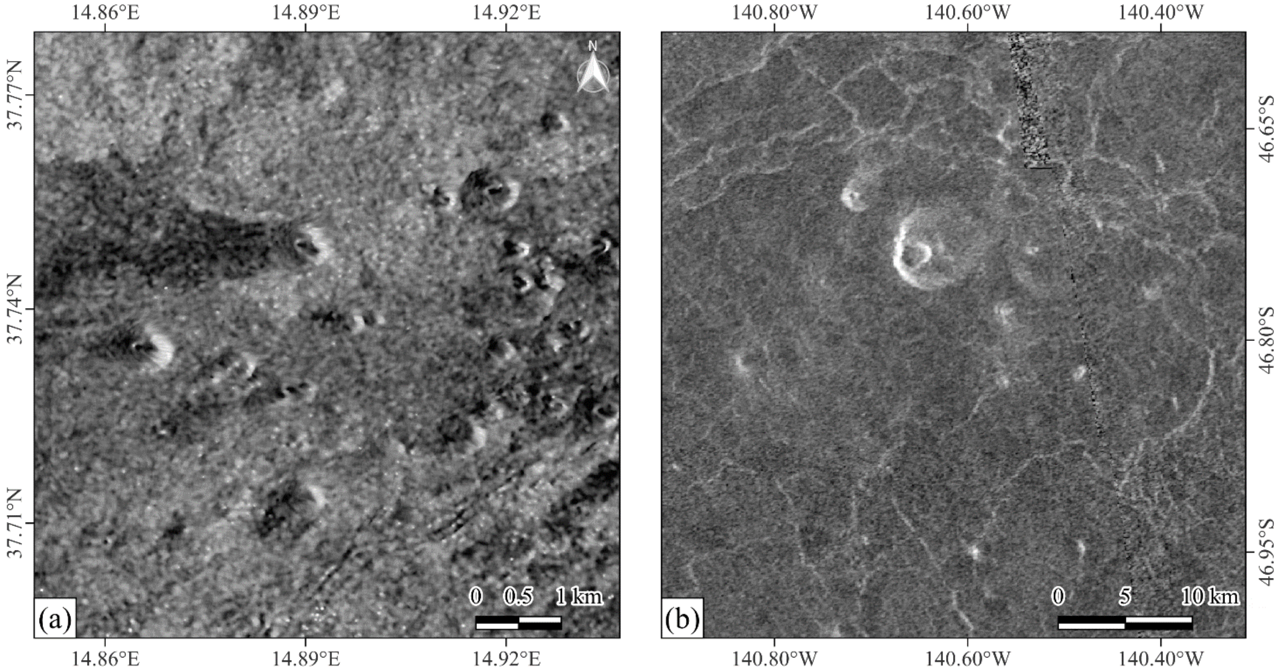

Figure 3: a) Cinder cones on the western flank of Mt. Etna. ESA Sentinel-1A C-Band, GRDH SAR Ascending - Resolution ~21m. b) Shield volcanoes in Imdr Regio - Venus. Magellan left-look SAR scene (S-band, total power HH pol), resolution ~75m.

3.3 Structural context: volcano-rift systems as an indicator for recent activity

Mount Etna is characterized by a direct interaction with a rift system related to the WNW-ESE oriented regional extensional regime (Monaco et al. 1997, 2005; 2021; Gambino et al. 2022). The main eruptive fissures cut the north-northeastern and south flanks of the volcano, forming two major rift zones (Azzaro et al. 2012) mostly oriented SW-NE (the NE Rift) and NNW-SSE (the S Rift), respectively (Figure 4a). Some other eruptive fissures and alignments of volcanic vents are radially distributed on the western slope of the volcano (Patanè et al 2011). Northeast of the summit craters, along the NE Rift, WNW-ESE regional extension is accommodated by pure opening (Monaco et al., 1997). The NE Rift is associated with over 60 linear surface ruptures and clusters of monogenetic cones (Tibaldi et al. 2021). The occurrence of the central conduit can be related to the maximum extension occurring in correspondence of the summit crater area. Here, the cracking system of the S Rift, located south of the summit craters and characterized by less ordered distribution of fissures and

cones, turns from a N-S to a SW-NE direction. The overall geometry of this rift zone, which is considered the main feeding system of the volcano (Patanè et al. 2006; 2011; Giacomoni et al. 2012), implies a right-lateral component of motion (Monaco et al., 1997; 2005).

Similar to Mount Etna, Idunn Mons on Venus (as well as several other large volcanoes) is characterized by the direct interaction with Olapa Chasma, a rift system extending NW-SE of Idunn Mons (Figure 4b). On Venus, volcano-rift systems represent the geologically most recent areas of the planet (i.e., D'Incecco et al. 2020).

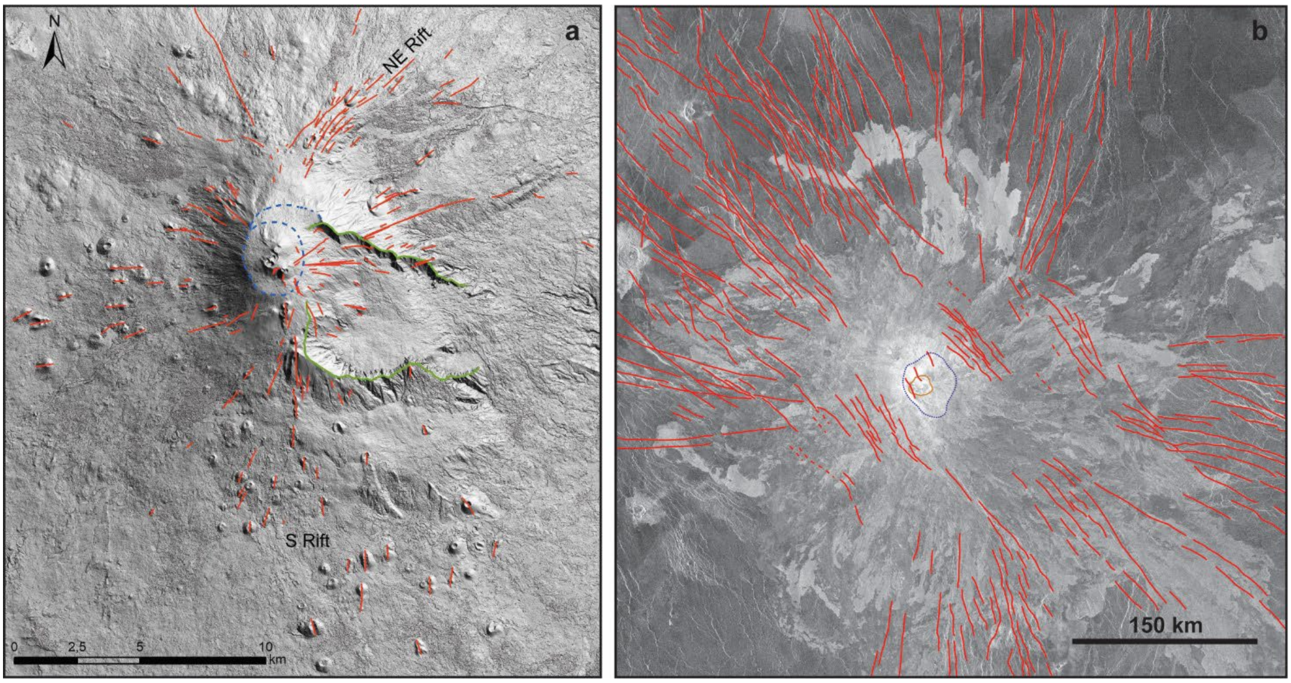

Figure 4: Structural context of a) Mount Etna (adopted from Monaco et al. 2021 and Barreca et al. 2018) overlayed a hillshade DSM (Palaseanu-Lovejoy et al. 2019), and b) Idunn Mons overlayed on Magellan SAR mosaic (structures adopted from López et al. 2022). Legend for a) Dashed blue line: buried caldera rim. Continuous green line: collapse rim. Continuous red line: volcano-rift eruptive fissures. Legend for b) Dashed blue line: flat topped summit. Dashed yellow line: summit caldera collapses. Continuous red line: volcano-rift structural lineaments.

4. Mount Etna as a suitable terrestrial analog site for infrared spectral analyses

Based on the observations by the Visible and Infrared Thermal Imaging Spectrometer (VIRTIS) instrument mounted on the ESA Venus Express spacecraft, Smrekar et al. (2010) identified model-based high 1 μm surface emissivity anomalies over the summit and eastern flank of Idunn Mons, suggesting chemically unweathered surface deposits and, by consequence, possibly recent volcanic activity. Smrekar et al. (2010) proposed the youngest flows at Idunn Mons to be 2.5 million years old or possibly even 250,000 years old or younger, which was largely based on predicted alteration rates for the Venus crust. These observations were also confirmed by Brossier et al. (2020, 2021, 2022) using Magellan global radar emissivity anomalies occurring at Idunn Mons itself, as well as other potentially active volcanoes on Venus at scales of tens of km. However, to constrain the age of 'fresh' lava flows, alteration rates were needed that were experimentally determined at Venus specific conditions (e.g., Dyar et al. 2020). Recent laboratory studies at Venus applicable conditions have shown that basalt in contact with the caustic Venus deep atmosphere should alter quickly – on experimental time scales of days to years (Berger et al. 2019; Cutler et al. 2020; Fegley et al. 1995; Filiberto et al., 2020; Knafelc et al., 2019; Reid et al. 2021; Teffeteller et al. 2022; Radoman-Shaw et

al. 2022 – see recent review Filiberto and McCanta 2023). Combining these experimental results, with geochemical modeling (Zolotov 2018; Semprich et al. 2020), suggests that surface materials on Venus should be coated with iron-oxides (hematite and/or magnetite) and Ca-, K-, and/or Na-sulfates; however, the exact mineral chemistry and rate of alteration depends on both the physical properties of the basalt (including composition, crystallinity, grain size), and specific composition (including S and O fugacity) of the atmosphere (Filiberto and McCanta 2023). These surface coatings should be measurable by orbital spectroscopy once they reach ~ 30 um (Dyar et al. 2020), which is suggested to occur after years to ~10,000 years (Filiberto et al. 2020; Cutler et al. 2020; Reid et al. 2021; Teffeteller et al. 2022; Filiberto and McCanta 2023). Therefore, the suggested fresh unweathered basalts on the summit and eastern flank of Idunn Mons are likely ~10,000 years old or younger.

Given its composite nature, Mount Etna can be considered as a suitable, yet imperfect, site for the analysis of the Visible-to-near-infrared reflectance spectral signatures of both effusive and explosive eruptive products. Using a Spectral Evolution OreXpress spectrometer, our ongoing work is analyzing the spectral features of several lava flow samples from Mount Etna (both a'a' and pāhoehoe), in the 0.5 – 2.5 micron range (Eggers et al., 2022; 2023). Eggers et al. (2022; 2023) preliminary data show that younger, and therefore less weathered, basalts have low reflectance and thus high emissivity values, while older samples have higher reflectance and thus lower emissivity values, which is as predicted based on experimental results (Fegley et al. 1995; Dyar et al. 2020; Filiberto et al. 2020). Further, younger basalts have spectra more consistent with igneous minerals like olivine and pyroxene, while older basalts are consistent with alteration minerals dominated by Fe^{3+}, which is consistent with experiments run under Venus conditions that show iron oxidation (e.g., Filiberto and McCanta 2023). Ongoing work will constrain the mineralogical changes associated with these spectral features and how these compare with previous experimental and modeling studies.

5. Mount Etna as a test area for future Venus Missions

Here, we provide two examples of how Mt Etna could be used as a test bed for future Venus missions – a lander and an orbital radar.

5.1 Future landing missions to Venus: Drilling Operational Tests

The past Soviet Venera and Vega missions have landed, largely, on lower roughness rolling plains (Garvin et al. 1984; Basilevsky & Head 1995; Kargel et al. 1993). Venera-13 and 14, as well as Vega-2, provided our only direct chemical analyses (XRFS elemental analyses) of the Venusian crust and revealed a range in basaltic compositions consistent with tholeiitic and alkalic basalts (Surkov et al., 1984; Filiberto, 2014; Kargel et al., 1993). For the Venera-D mission, D'Incecco et al. (2021c) proposed to move beyond landing on volcanic plains units to the young volcanic terrain such as Idunn Mons; however, that would also potentially increase the landing risk of Venera/Vega class systems. The past Soviet Venera missions never performed landing safety or drilling mechanism tests on analog sites on Earth before the launch. However, if we want to specifically target a potentially active volcanic structure of Venus as the landing site for the Venera-D mission (as well as other future landing missions to Venus), we need to carefully test the safety conditions on the landing area, such as the lander-scale slope and the expected roughness of lava flows (a'a' vs pāhoehoe). Because of its potentially comparable morphology and chemical composition of the surrounding lava flows, Mount Etna can be used as a site for drilling operations, sample recovery and distribution, and in-situ geochemical analyses as tests planned to be performed by a future Venus lander.

5.2 Future orbital missions to Venus: Radar Observations

As an example of data products from future orbital radar missions, we characterize the extensive and compound lava flows along the western flank of Mt. Etna using the high-resolution fully polarimetric C-band (wavelength 5.3 cm) SAR data of this region obtained by RISAT-1A instrument on board EOS-4 mission (Putrevu et al., 2020) by the Indian Space Research Organization (ISRO). This SAR instrument has various imaging modes to cater to several resolution and swath requirements, and here we utilized the Fine Resolution Stripmap-2 (FRS-2) mode data which was obtained with a scene centre incidence angle of 35.4° and at a slant range pixel spacing of 2.3m×3.6m (azimuth × range). After processing the data with 3 azimuth looks and averaging it further with a 5×5 boxcar filter to reduce the speckle-related uncertainties, the final ground-range data has a spacing of 4 m/pixel. The quad-polarization mode RISAT-1A data captures the full scattering matrix for each pixel, allowing synthesis of any combination of transmit and receive polarizations, as well as several useful products such as the circular polarization ratio (CPR) and polarimetric decompositions. The CPR, which is the ratio of the power in the circular polarization transmitted and received in the same rotation sense (SC) to the power in the circular polarization transmitted in one rotation sense and received in the opposite sense (OC), provides significant information about the physical properties of the surface and near subsurface (i.e., Campbell 2012). We have observations of CPR in a wide range of terrestrial (i.e., Campbell et al. 1993; Plaut et al. 2004) and planetary settings including Venus (Campbell et al., 1999; Carter et al., 2004). Indeed, analyses of high-resolution Magellan and Arecibo data for Venus revealed that the low-emissivity (high reflectivity) surfaces on portions of the planet above ~6053 km radius (Pettengill et al. 1992) exhibit highly variable CPRs, which in some cases exceed unity (Campbell et al. 1999).

The co-pol (HH, Figure 5a) and cross-pol (HV, Figure 5b) data distinctly highlight the progression of dated lava flows associated with this composite volcano, which exhibit a wide range of textures (Figure 5). While a portion of the most recent flows appear radar-bright in HH-pol data (lower center in Figure 5a), they are uniquely separated in HV-pol data (Figure 6b) and have lower CPR values as shown in Figure 6a. A Yamaguchi 4-component decomposition image (Yamaguchi et al., 2005) indicates that surface scattering (blue) is the dominant scattering contribution from this region (Figure 6b), implying a relatively smooth surface. In contrast, a large lava flow region (central portion of Figures 5,6) that is radar-bright in HV-pol data, and almost every flow channel associated with the cinder cones visible in Figures 5,6 have elevated CPRs (1 and above) along with a high degree of volume/diffuse scattering components (green in Figure 6b) indicating blocky, a'a type of textures. The elevated CPRs could be a result of diffuse scattering between randomly oriented dipole elements (rock edges and ground cracks) and/or dihedral scattering from features such as tilted plates and closely spaced boulders (i.e., Campbell 2012). Since the CPR of randomly oriented dihedral features will rise with the real dielectric constant, field probe measurements of real dielectric constant would provide further insights into the types of scattering processes associated with these flows.

This analysis was done to show the potentials of a quad pol SAR instrument for Venus, but not for a direct comparison of (S-band) Magellan results to those obtained from a C-band SAR instrument.

Fully polarimetric SAR images can provide crucial information on the target surface when compared to single/dual-polarized SAR data. The central objective here in using RISAT-1A data was to showcase the abilities of fully polarimetric data in highlighting the change of textures and surface roughness associated with different types of lava flows associated with terrestrial volcanoes.

This analysis of a portion of Mt. Etna lava flows is meant to show how the fully polarimetric SAR data are can help to understand their geologic properties and serve as a precursor to similar kind of studies being planned for Venusian volcanic landforms using orbital S-band fully polarimetric SAR on board ISRO's future Venus's mission.

However, more detailed investigations focusing on the identification of the possible correlations between surface texture of the lava flows and their age (Campbell et al. 1993) will be pursued during the future field trip campaigns on other analog volcanic structures (i.e. Kilauea) to be selected within the AVENGERS initiative (D'Incecco et al. 2022, 2023).

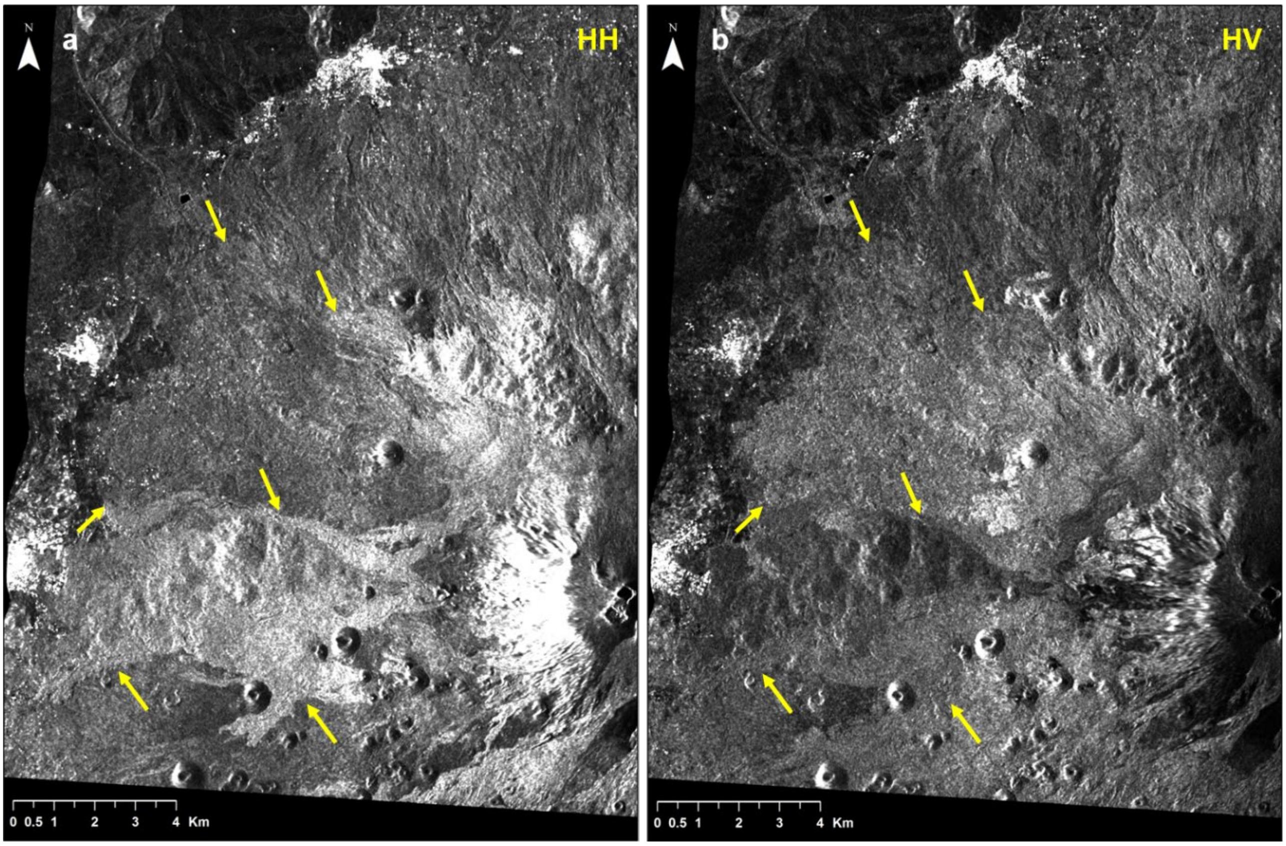

Figure 5: RISAT-1A C-band (wavelength 5.3 cm) SAR data of Mt. Etna region shown here in a) HH, b) HV polarizations at 4m /pixel resolution. Arrows highlight the extents and boundaries of historical and recent lava flows that have a suite of textures (a'a to pāhoehoe). Notice the high degree of unit discrimination in the HV-pol data compared to the HH-pol data, since the HV-pol echoes are more sensitive to surface roughness at all incidence angles.

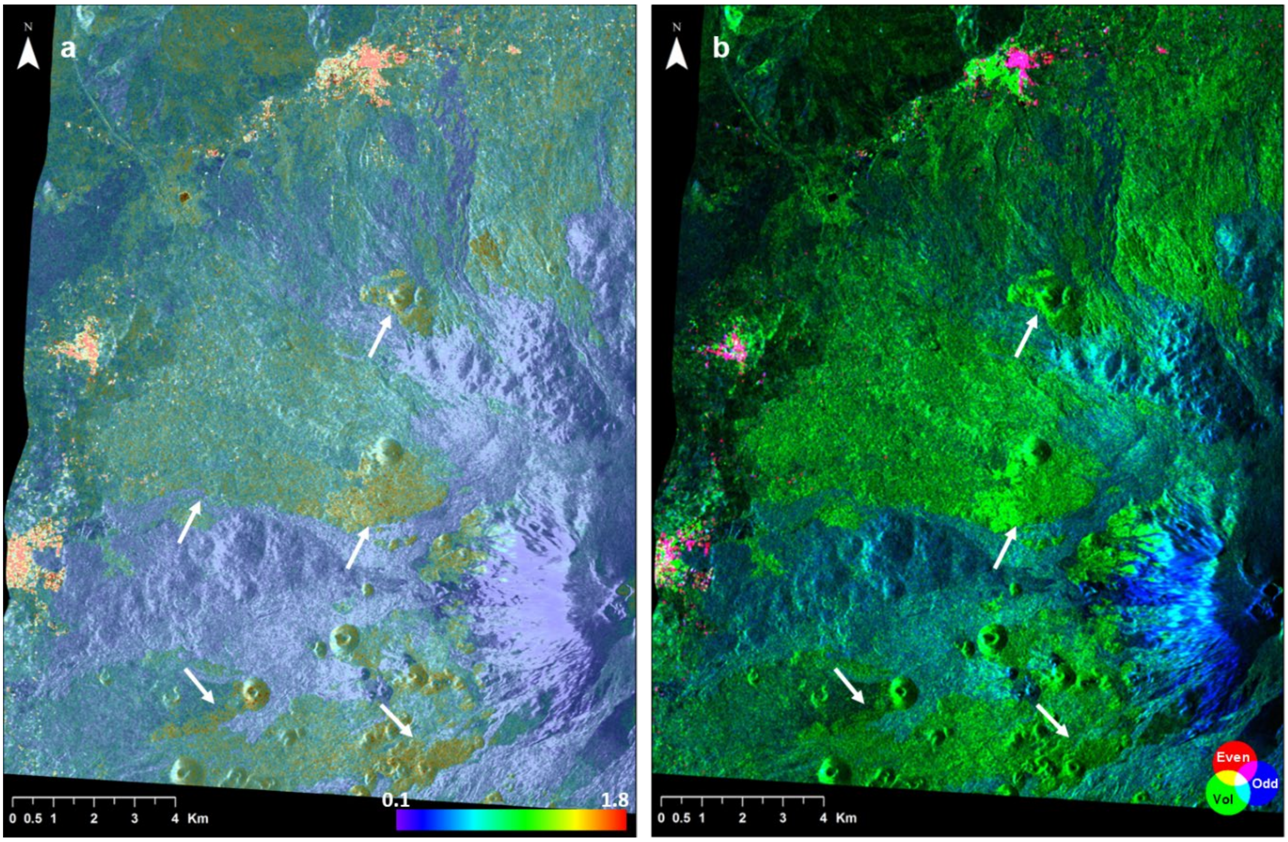

Figure 6: Mt. Etna region shown here in a) circular polarization Ratio (CPR) and b) Yamaguchi 4-component decomposition images. These polarimetric products are generated from RISAT-1A C-band SAR data at a resolution of 4 m/pixel. The CPR image is stretched to a colour scale and overlaid on HH-pol data and the colour wheel in the decomposition image (b) highlights the colours for each scattering regime (red: even bounce; blue: single (odd) bounce; green: volume scattering). Flow channels with CPR values of above 1 are mostly associated with cinder cones, indicated with arrows in both a and b. These flows have most likely a'a textures and have a high degree of surface roughness due to diffuse/volume scattering (green regions in b) from blocks on the order of at least a few radar wavelengths.

6. Conclusions

The wealth of data to be provided by future missions will address major scientific conundrums about the geologic evolution of Venus, including the possible occurrence of ongoing volcanism and related eruptive style (Shalygin et al. 2015; Smrekar et al. 2020; D'Incecco et al. 2017, 2021a, 2022; Filiberto et al. 2020, 2021; Teffeteller et al. 2022; Brossier et al. 2020, 2021, 2022; Herrick & Hensley 2023). For this reason, it is crucial to exploit active volcanoes on Earth for analyses of comparative geology to identify and study possible active volcanoes on Venus, such as Idunn Mons.

We proposed here Mount Etna as a first suitable analog, given the ease of access, its variety of volcanic products, and for the morphologic similarities between the cinder cones surrounding this volcano and the shield fields surrounding Idunn Mons and other portions of the surface of Venus.

However, Mount Etna and Idunn Mons also differ under several aspects, including in particular their topography (relatively steep slopes characterize the flanks of Mount Etna, while much gentler slopes characterize Idunn Mons) and their summit area, with the summit of Idunn Mons being more suitably comparable to the summit hot-spot shield volcanoes such as Kilauea in Hawaii.

It is important to remember that there is no perfect analog in the Solar System, especially when comparing volcanic structures on two or more planetary bodies characterized by different internal processes and surface environmental conditions. For this reason, it will be fundamental to select and

analyze several suitable analogs on Earth, because each terrestrial analog can help us to better study and understand some specific aspects of the current volcanic activity on Venus. Indeed, each suitable analog on Earth can reveal to us a part of the volcanic history of Venus.
To this regard, the proposed analysis of Mount Etna can be considered as the first step of the AVENGERS initiative, that will indeed select and analyze suitable analog volcanic structures on Earth for the analysis and identification of active volcanism on Venus (D'Incecco et al. 2022, 2023).

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